

imaging system B so that the ratio of the numerical apertures of an irradiation optical system to the catadioptric projection system  $\sigma$  can be easily varied. Third, by increasing the number of lens elements in the second imaging system B, the numerical aperture of the catadioptric projection system according to the invention can be increased. Fourth, re-imaging the intermediate image by the second imaging system B provides a long working distance. Fifth, the catadioptric projection systems of the invention are compact. Finally, because light reflected from the concave mirror  $M_1$  is returned near the focused image, off-axis lens aberrations are reduced.

With the additional turning mirrors of the second and third example embodiments, the relative orientations of the reticle R and the wafer W can be adjusted. I.e., the second example embodiment, the reticle R and wafer W are parallel to each other and on the same optical axis. In the third example embodiment, the reticle R and the wafer W are parallel to each other but are situated on offset but parallel optical axes. Thus, the present invention permits orienting the reticle R and the wafer W in a way allowing simplification of the scanning systems.

The catadioptric projection systems of the example embodiments also permit the turning mirrors to closely approach the respective optical axes. Therefore, light reflected by the concave mirror  $M_1$  back through the doublepass lens group  $A_2$  is easily separated from the light propagating from the single-pass lens group  $A_1$  to the double-pass lens group  $A_2$ . Because the turning mirror or mirrors are situated close to the respective optical axes, light need not propagate at large angles with respect to the optical axes and off-axis aberrations are reduced. Prior-art systems often require angles of  $20^\circ$  or more while the catadioptric projection systems of this invention use angles no greater than about  $10^\circ$ .

Some prior-art scanning projection systems expose an annulus of the wafer from a corresponding annular illuminated region of the reticle. The reticle and wafer are scanned at different speeds corresponding to the magnification of the optical projection system. Because such scanning exposure systems expose only small areas of the wafer W at any give instant, complete exposure of the wafer W requires many incremental exposures. If the light from a radiation source is used inefficiently, exposure times will be long. Because the catadioptric projection systems of this invention do not require large angles for separating light incident to and exiting from the concave mirror, the catadioptric projection systems can have high numerical apertures, thereby reducing exposure times.

Because the first imaging system A and the second imaging system B are independent of each other, manufacture and alignment are simple.

Having illustrated and demonstrated the principles of the invention in a example embodiments, it should be apparent to those skilled in the art that the example embodiments can be modified in arrangement and detail without departing from such principles. I claim as the invention all that comes within the scope of these claims.

What is claimed is:

1. A catadioptric projection system for receiving light from a reticle and projecting a pattern from the reticle onto a substrate, the catadioptric projection system comprising:
  - a first imaging system that forms an intermediate image of an illuminated region of the reticle, the first imaging system comprising in order from the reticle and along an optical axis of the first imaging system,
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single-pass lens group comprising a first negative subgroup, a positive subgroup, and a second negative subgroup, and (b) a double-pass lens group comprising a concave mirror, wherein light from the illuminated region of the reticle passes through the single-pass lens group and the double-pass lens group, reflects from the concave mirror, and returns through the double-pass optical group; a first turning mirror placed near the intermediate image that receives the light reflected by the concave mirror to and returned through the double-pass optical group; and a second imaging system that receives the light reflected by the first turning mirror and that re-images the intermediate image to form a final image of the illuminated region of the reticle on the substrate.

2. The catadioptric projection system of claim 1, wherein the first negative subgroup of the single-pass lens group comprises a lens element with a concave surface facing the reticle.

3. The catadioptric projection system of claim 1, wherein the second negative subgroup of the single-pass lens group comprises a lens element with a concave surface facing the double-pass lens group.

4. The catadioptric projection system of claim 1, wherein the second negative subgroup of the single-pass lens group comprises a lens element with a concave surface facing the double-pass lens group.

5. The catadioptric projection system of claim 1, wherein either the first imaging system or the second imaging system produces a magnification of less than one.

6. The catadioptric projection system of claim 1, wherein the second imaging system comprises a first lens group and a second lens group, the system further comprising a second turning mirror placed between the first lens group and the second lens group and that receives light from the first lens group and directs the light to the second lens group.

7. The catadioptric projection system of claim 1, further comprising a third turning mirror placed between the single-pass lens group and the double-pass lens group and that receives light from the single-pass lens group and directs the light to the double-pass lens group.

8. The catadioptric projection system of claim 7, wherein the third turning mirror and the first turning mirror are arranged so that the light incident to the single-pass optical group and exiting the second lens group of the second imaging system propagate along substantially parallel axes.

9. The catadioptric projection system of claim 8, wherein the first axis and the second axis are colinear.

10. A catadioptric projection system for receiving light so from a reticle and projecting a pattern from the reticle onto a substrate, the catadioptric projection system comprising:

a first imaging system that forms an intermediate image of an illuminated region of the reticle, the first imaging system comprising from objectwise to imagewise, (a) a single-pass lens group comprising a first negative subgroup, a positive subgroup, and a second negative subgroup, and (b) a double-pass lens group comprising a concave mirror, wherein light from the illuminated region of the reticle passes through the single-pass lens group and the double-pass lens group, reflects from the concave mirror, and returns through the double-pass lens group;

a first turning mirror placed near the intermediate image, the first turning mirror separating the light propagating from the double-pass lens group from the light propagating to the double-pass lens group; and

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(b) transmitting light from the reticle through the single-pass lens group and the double-pass lens group to the concave mirror, and returning the light reflected from

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(c) separating the light propagating through the doublepass lens group to the concave mirror from the light propagating through the double-pass lens group from the concave mirror;

(e) directing the light propagating from the concave mirror through the second imaging system; and

(f) forming an image of the reticle on the substrate with the second imaging system.

20. The method of claim 19, further comprising directing the light, reflected by the concave mirror and returning through the double-pass lens group, to the second imaging system using a second turning mirror.

22. The method of claim 21, further comprising orienting the first turning mirror and the second turning mirror so that the light incident to the first turning mirror and the light reflected by the second turning mirror propagate along substantially the same axis.

23. The method of claim 18, further comprising:  
providing a first turning mirror placed between the single-pass lens group and the double-pass lens group; and  
directing light, returning through the double-pass lens group from the concave mirror, to the second imaging system using the first turning mirror.

24. The method of claim 23, further comprising:  
providing the second imaging system with a first lens group  
and a second lens group;  
providing a second turning mirror between the first lens group  
and the second lens group; and

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wherein the first optical axis and the second optical axis are not parallel to each other, and the reticle and the substrate are arranged to be parallel to each other.

a second optical subgroup comprising the concave mirror and the first optical axis.

30. A catadioptric imaging optical system according to claim 28, wherein the second optical subgroup comprises a negative lens and a positive lens.

32. A catadioptric imaging optical system according to claim 27, wherein the image formed by said catadioptric imaging optical sub-system is a primary image of the pattern on the reticle.

33. A catadioptric imaging optical system according to claim 27, further comprising a first turning mirror arranged in an optical path between the concave mirror and said dioptric imaging optical sub-system.

34. A catadioptric imaging optical system according to claim 33, further comprising a second turning mirror arranged in an optical path between the concave mirror and the reticle.

a first subgroup comprising a third optical axis, and  
a second subgroup comprising the concave mirror  
and the first optical axis.

36. A catadioptric imaging optical system according to claim 35, wherein the third optical axis and the second optical axis intersect.

a catadioptric imaging optical system according to claim 27, said catadioptric imaging optical system forms an

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43. A projection exposure apparatus according to claim 42, wherein the reticle and the substrate are scanned at different speeds corresponding to the magnification of said catadioptric imaging optical sub-system.

✓ 44. A method of imaging a pattern on a reticle onto a substrate, comprising:

passing a light from the reticle through a first optical group comprising a lens with a first optical axis;

forming an intermediate image by a light passing through the first optical group and a second optical group, the second optical group comprising a concave mirror with a second optical axis; and

guiding a light having passes through the second optical group to the substrate by passing the light through a dioptric imaging optical sub-system with a third optical axis,

wherein the first optical axis and the second optical axis intersect, and

wherein the second optical axis and the third optical axis intersect.

44 45. A method according to claim 44, wherein in said forming comprises forming a primary image of the reticle.

46. A catadioptric imaging optical system used in a projection exposure apparatus that transfers a pattern on a reticle onto a substrate, comprising:

a first turning mirror arranged in an optical path between the reticle and the substrate;

a concave mirror arranged in an optical path between said first turning mirror and the substrate;

a second turning mirror arranged in an optical path between said concave mirror and the substrate; and

a dioptric imaging optical sub-system arranged between said second turning mirror and the substrate and comprising an optical axis,

wherein the reticle and the substrate are arranged to be parallel to each other.

47. A projection exposure apparatus that transfers a pattern on a reticle onto a substrate, comprising a catadioptric imaging optical system according to claim 46, wherein said catadioptric imaging optical system forms the pattern on the reticle off of the optical axis onto an exposure region on the substrate off of the optical axis.

48. A projection exposure apparatus according to claim 47, wherein the reticle and the substrate are scanned at different speeds corresponding to the magnification of said catadioptric imaging optical system.

✓ 49. A method of imaging a pattern on a reticle onto a substrate, comprising:

reflecting a light from the reticle with a first turning mirror;

reflecting the light from the first turning mirror with a concave mirror;

reflecting the light from the concave mirror using a second turning mirror; and

passing the light from the second turning mirror to the substrate through a dioptric imaging optical sub-system having an optical axis,

wherein  
an intermediate image of the pattern is formed in an optical path between the concave mirror and the dioptric imaging optical sub-system,

an image of the intermediate image is formed on the substrate by the dioptric imaging optical sub-system, and

the reticle and said substrate are arranged in parallel to each other.

<sup>51</sup> ~~50~~ A method according to claim ~~49~~<sup>50</sup> wherein said intermediate image is a primary image of the reticle.

~~51~~ A catadioptric imaging optical system according to claim 29, wherein the second and third optical axes form a straight optical axis.

~~52~~ A catadioptric imaging optical system according to claim 31, wherein the first and third optical axes are parallel to each other.

~~53~~ A catadioptric imaging optical system according to claim 52, wherein the first and third optical axes form a straight optical axis.

~~54~~ A method according to claim 44, wherein the first and third optical axes are parallel to each other.

55. A method according to claim 54, wherein the first and third optical axes form a straight optical axis.

~~56~~ A catadioptric imaging optical system according to 46, wherein the optical axis of said dioptric imaging optical sub-system forms a straight line.

~~57~~ A method according to claim 49, wherein the dioptric imaging optical sub-system comprises an optical axis along a straight line.

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